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# RESEARCH ON A BASIC STUDY OF THE HIGH-SPEED PENETRATION DYNAMICS OF TEXTILE MATERIALS

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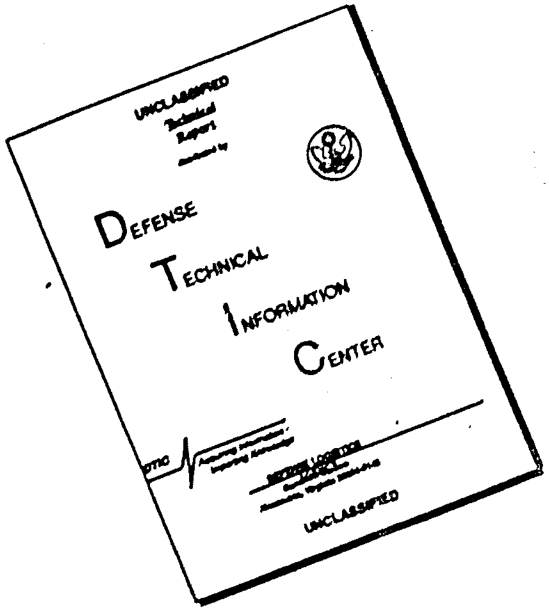


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# RESEARCH ON
# A BASIC STUDY OF THE HIGH-SPEED PENETRATION DYNAMICS OF TEXTILE MATERIALS

FINAL TECHNICAL REPORT

by

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The work described in a previous report has been extended to cover the effect of target diameter and backing material on penetration and energy absorption using a selection of the materials studied previously. The influence of change of target diameter is related to a simple theoretical treatment of penetration mechanics. The theoretical and experimental results confirm the importance of the shape of the stress-strain curve. Yielding materials give (Contd)

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20. Abstract (Cont'd)

a high localised deformation with poor strain propagation and energy absorption, while locking materials give good strain propagation and energy absorption. A review of the work carried out under the current as well as previous contracts is presented and related to the history of research in the topic area to include a comparison of theoretical approaches and suggested direction for future research.

## Contents

## List of figures

## Chapter 1

## Introduction

The present report describes two main areas of investigation: (a) the influence of the shape of the stress-strain curve on effectiveness of energy absorption; (b) the effect of providing a backing material on ease of penetration.

In the previous report, it was stated that the shape of the load-deformation curve of the target material in a tensile test has a predominant effect on the energy absorption of the target in penetration. The reason for this effect, as discussed previously, is the dependence of strain propagation on the shape of the tensile load-deformation curve. So, it has been the aim of the work described in this report to investigate experimentally and theoretically the relation between the shape of the tensile load-deformation curve and the ability of the target to propagate the strains and absorb the energy due to penetration.

The influence of having a deformable backing behind the target was studied by testing targets from different materials supported by rubber sheets. This test simulates the use of the fabric in a garment backed by other fabrics and the body.

# Chapter 2

## STRAIN PROPAGATION IN THE TARGET

## A - EXPERIMENTAL STUDY

### Introduction

The principle on which the investigation of strain propagation has been based is to test the effect of reducing the target diameter on the amount of energy absorption in both the slow penetration test and the impact penetration test. If the reduction in target diameter causes a considerable reduction in the amount of energy absorption, this indicates that the target material propagates the strains to a great extent through the target. But if the reduction in target diameter causes little reduction in the amount of energy absorption by the target, this shows that the target material propagates the strains only to a very limited extent, with most of the energy absorption in the zone close to the penetration point. In other words, the slope of the relationship between target diameter and the absorbed energy could be taken as an indication of the degree of strain propagation in the target material. The higher this slope is, the higher is the ability of the material to strain propagation.

### Experimental method

#### 1 - Slow penetration test

A series of targets with successively decreasing diameter (15.25, 10, 5 and 2.5 cm) has been tested in slow penetration on the Instron, using the attachment described previously[1]. The fabric specimen was clamped between a pin of square clamping plates having a hole with the required target diameter. The recorded load-deformation curve was analysed to calculate the penetration strength, the maximum penetration bulge, and the energy absorbed in penetration. This test has been carried out for six different materials from the selection tested previously,

namely:

a - Polyethylene sheet 200 $g/m^2$

b - Spun-bonded polyester fabric 106 $g/m^2$

c - Spun-bonded polypropylene fabric 110 $g/m^2$

d - Needled Nylon felt 230 $g/m^2$

e - Woven Nylon fabric 116 $g/m^2$

f - Warp knitted nylon fabric 85 $g/m^2$

## 2 - Impact penetration test

A series of targets with successively decreasing diameter, similar to the series in the above test, has been tested in impact penetration on the ballistic equipment(1). The above sixmaterials have been tested in this method, for comparison purposes with the slow penetration test.

## Results and discussion

### 1 - Slow penetration test

### Effect of target diameter on penetration strength

Fig. (1) shows that the reduction in target diameter has no appreciable effect on the penetration strength. However, in some materials, such as the needle felt, the penetration strength tends to increase when the target diametor is reduced to 2.5 cm. This could be related to the minimised fibre slippage in the needle felt at the small target diameter, which contributes to a higher penetration strength. But in the case of materials which do not involve fibre slippage, such as paper, the penetration strength depends mainly on the pellet diameter, and accordingly it will be fairly constant at the different target diameters.

**Effect of target diameter on maximum penetration bulge.**

From Fig. (2) it can be seen that the decrease of target diameter causes a significant decrease in the maximum penetration bulge. The rate at which the maximum bulge decreases differs according to the type of material. This rate of decrease in the maximum bulge is higher in the case of the needle felt, the knitted fabric, and the woven fabric than in the case of spun-bonded fabric, polyethylene, and paper. This difference in behaviour can be explained in terms of the difference in the ability of strain propagation between the two groups of materials. In the case of the first group, the material has a steepening load-deformation curve which enables the strains to be propagated through the target. On the other hand, the second group has an elastic-plastic load deformation curve which does not provide efficient strain propagation.

It can also be deduced from fig. (2) that the higher the stiffness of the material, the lower is its maximum penetration deformation and the lower the effect of reducing the target diameter on this deformation.

**Effect of target diameter on penetration energy**

Fig. (3) shows the effect of reducing the target diameter on the energy absorption in slow penetration for both the locking and the non-locking groups of materials. It can be clearly seen that the locking materials show a considerable reducing in energy absorption by the reduction of target diameter. On the other hand, the stiff non-locking materials do not show substantial reduction in energy absorption by the reduction of target diameter. These results are, in fact, a reflection of the results obtained on the maximum bulge, because the penetration strength is not materially affected by the reduction of target diameter. It can be concluded that the target diameter is an important parameter determining the amount of energy absorption, only in the case of the locking materials; but in the case of stiff non-locking materials, the increase of target

diameter does not add substantial increase in energy absorption. In other words, in the material which provides a higher degree of strain propagation, its ability to absorb energy is more influenced by the target diameter than a material with a lower degree of strain propagation.

## 2 - Impact penetration test

Fig. (4) shows the effect of reducing the target diameter on the absorption of energy in impact penetration for both the locking and non-locking groups of materials. It can be seen that the effect obtained in this case is similar to that obtained in the slow penetration test. The locking materials show a considerably higher rate of response to the reduction in target diameter than the non-locking materials. This shows that the material which has a high degree of strain propagation in slow penetration, will have also a high degree of strain propagation in impact penetration. And therefore, the tensile load-deformation curve of the material could be taken as an indication of the material ability for strain propagation in impact penetration. And the effect of reducing the target diameter, in slow penetration, on the energy absorption could also be taken to predict qualitatively the behaviour of the material in impact penetration.

### 3 - Impact penetration on composite targets

Fig. (5) shows the effect of combining a locking fabric (knitted nylon) with a non-locking fabric (spun-bonded polypropylene) on the energy absorption of the target. It appears that when the locking knitted structure is backed with a non-locking spun-bonded structure, the energy absorption of the knitted target is considerably reduced. This could be related to the obstruction to strain propagation caused by the stiff backing, as can be seen by comparing the rate of reduction in energy absorption of the composite target with that of the knitted target. This rate is lower in the case of the composite target, indicating a lower degree of strain propagation.

When the stiff non-locking fabric is backed with the locking knitted fabric, the energy absorption of this stiff fabric is considerably improved especially at the large target diameter of 15.25 cm. but the energies are still generally less than that of the knitted fabric above.

## B - THEORETICAL STUDY

### Introduction

This theoretical study has been attempted to investigate the effect of the shape of the tensile load-deformation curve of the target material on the type of deformation of the target in slow penetration. Also it has been aimed to predict the effect of the tensile work factor on the material ability for strain propagation, and compare this theoretical effect with the experimental effect achieved previously in both the slow penetration test and impact penetration test.

## Theory

The target is assumed to be divided into a number of concentric zones, each zone with a width equal to the pellet diameter $d = 5$ mm., as illustrated in fig. (6). So the number of zones in the target with a diameter 152.5 mm is approximately 15 zones.

## Zonal/Stress

At the moment of penetration, the stress at the centre of the target will be equal to the breaking stress of the target material $f_b$. Moving radially from the centre to the boundary of the target, the zonal stress $f_z$ decreases gradually, and it is given by:

$$f_z = f_b \times \frac{d}{D_z} \qquad (1)$$

where d = pellet diameter

$D_z$ = Zone Centre diameter.

## Zonal strain

The zonal strain can be calculated from both the zonal stress in equation (1), and the idealised stress-strain curve of the target material. The idealised stress-strain curve consists of two sections of different slope defined as illustrated in fig. (7) by

$f_y$ = yield or locking stress (g.wt/tex)

$e_y$ = yield or locking strain (dimensionless)

$f_b$ = breaking stress (g-wt/tex)

$e_b$ = breaking strain (dimensionless)

If the zonal stress $\leqslant f_y$, the zonal strain is given by

$$e_z = f_z \frac{e_y}{f_y} \qquad (2)$$

where $f_z$ = zonal stress calculated from equation (1)

But if the zonal stress $> f_y$, the zonal strain is given by:

$$e_z = (f_z - f_y) \frac{(e_b - e_y)}{(f_b - f_y)} + e_y \qquad (3)$$

So, from equations (1), (2) and (3) the strain at each individual zone throughout the target could be calculated.

## Zonal bulge

Having calculated the zonal strain $e_z$, the zonal bulge ($b_z$) can be calculated, according to fig. (8), from:

$$b_z = d \tan \theta$$

$$= d \sqrt{e_z^2 + 2e_z} \qquad (4)$$

## Calculations

### Deformed Shape of target

From equations (3) and (4) the bulge for each individual zone in the target can be calculated, moving from the centre to the boundaries. The cummulative addition of these individual bulges gives the total target penetration bulge. From the total bulge, and the individual zonal bulges, the deformed shape of the target at the moment of penetration could be plotted.

The above calculations have been carried out, on the computer, for different shapes of idealised stress-strain curves of target materials shown in fig. (9). The resulting shapes of the deformed targets at the moment of penetration are shown in fig. (10). It can

be seen from these shapes that as the work factor of the target material decreases, the maximum penetration bulge increases. This agrees with the previous experimental findings shown in the previous report[1]. It also appears from fig. (10,a), that although different target materials might have the same strength and breaking extension, their behaviour in penetration will be considerably different due to the difference in the shape of the stress-strain curves of these materials. And from fig. (10,b) one can deduce that if two materials have the same tensile work of rupture, but

different shapes of stress-strain curve, they will behave totally different regarding the energy absorption in penetration. In other words the tensile work of rupture is not a correct indication to energy absorption in penetration, as the shape of the curve has a very important effect on the behaviour of the target in penetration.

Comparing quantitatively the theoretical values of the maximum penetration bulge with the corresponding values obtained experimentally in the slow penetration test, a reasonable agreement has been found as illustrated in fig. (11).

## Strain propagation deduced from theory

The theoretical maximum penetration bulge has been calculated for targets with successively decreasing diameters, from materials with different tensile work factors as illustrated in fig. (12). It can be seen from this figure that the lower the work factor, the higher the rate of reduction in maximum penetration energy due to the reduction in target diameter. As this rate of reduction represents the ability of strain propagation in the target material in penetration, it can be deduced that the lower the work factor of the material, the higher its ability for strain propagation. This theoretical conclusion agrees well with the experimental conclusion obtained in the previous report. As has been previously discussed, the energy absorption in penetration increases

with the increase in strain propagation. So, the theoretical analysis could be considered useful, because it predicts the material ability for strain propagation in penetration, and consequently it predicts the material ability for energy absorption in penetration.

# CHAPTER 3

## Impact of Targets supported with rubber sheets

### Introduction

The work in this Chapter has been aimed to throw some light on the ability of the material to resist penetration into another material behind it. The different materials tested before have been tested in impact penetration after supporting them with rubber sheets. The behaviour of the target material in this test simulates the behaviour of the material used as pellet proof vests.

### Experimental method

The impact tests have been carried out on the ballistic equipment used in the previous tests, but after developing the steel stopping plate to be used as a specimen frame for the target as illustrated in fig. (13). In this frame, the fabric specimen was clamped after being supported with the required number of rubber sheets (1/16" thick). The frame was then fitted to the ballistic equipment, and secured to it by 4 wing nuts. The clamping plate, facing the gun had a hole with a diameter equal to the required target diameter.

A series of targets, supported by a successively increasing number of rubber sheets, starting from one sheet and finishing by the number of sheets causing bouncing of the pellet, has been tested in impact penetration at an impact speed 146 m/s. Similar series from different materials have been tested for the purpose of comparison. The observations on each individual test, regarding penetration, damage of backing and bouncing of the pellet, have been recorded for comparison.

Table (1) Impact of targets supported with rubber sheets (1/16")

| Type of target material | Number of rubber backing sheets | Observations after impact |
|---|---|---|
| 1) Polyethylene sheet 200g/m$^2$ | 1 | Both polyethylene and rubber backing were penetrated through and pellet was smashed on the surface of the stopping plate. |
| | 2 | Polyethylene penetrated through, and pellet contained in the two rubber backing sheets together. |
| | 3 | Pellet penetrated through polyethylene partly penetrated the first backing layer and contained by it, partly damaged the second backing layer and slightly damaged the third backing layer |
| | 4 | Pellet penetrated polyethylene, partly penetrated the first backing layer and contained by it, slightly damaged the second layer and did not damage the third or fourth layer. |
| | 5 | Pellet penetrated through polyethylene, partly damaged the first rubber layer and contained by it, and did not damage the remaining 4 layers. |
| | 6 | Pellet penetrated through polyethylene partly penetrated the first rubber layer and contained by it, but it did not damage the rest of the layers. |
| | 7 | Pellet bounced after pluging the poly-ethylene sheet, but it did not damage any of the rubber backing sheets. |
| 2) Spun bonded polyester nonwoven 106 g/m$^2$ | 1 | Pellet penetrated through both target and backing, and squashed on the surface of the stopping plate. |
| | 2 | Pellet penetrated through target, partly penetrated through the first backing layer and contained by it, and partly fractured the second layer. |
| | 3 | Pellet penetrated through target, partly penetrating the first backing layer and contained by it, and did not damage the second or the third layer. |
| | 4 | Pellet penetrated through target and bounced, and it caused a slight surface damage to the first backing layer only. |

| | Type of target material | Number of rubber backing sheets | Observations after impact |
|---|---|---|---|
| (3) | Warp knitted Nylon fabric 85 $g/m^2$ | 1 | pellet penetrated through both target and rubber backing, and it squashed on the surface of the stopping plate. |
| | | 2 | pellet penetrated through target, partly penetrated through first layer and contained in it, and damaged the second layer. |
| | | 3 | pellet penetrated through target, partly penetrated the first layer and contained in it, and it caused slight damage to the other two layers. |
| | | 4 | pellet penetrated through target and bounced, without damaging the backing layers. |
| (4) | Paper 77 $g/m^2$ | 1 | pellet penetrated through paper and rubber and it was squashed at the surface of the stopping plate. |
| | | 2 | pellet penetrated through paper, partly penetrated the first rubber layer and contained by it, and it damaged the second layer by punching it. |
| | | 3 | pellet penetrated paper and bounced, first backing layer slightly damaged, and rest of the layers not damaged. |
| (5) | Needle felt Nylon 230$g/m^2$ | 1 | pellet penetrated through the target and the rubber backing, and it was squashed at the surface of the stopping plate. |
| | | 2 | pellet bounced, damaged the fabric by fusion, but did not damage the rubber backing. |

| | Type of target material | Number of rubber backing sheet | Observations after impact |
|---|---|---|---|
| (6) | Woven Nylon 116 $g/m^2$ | 1 | pellet penetrated fabric, punched the rubber backing but did not penetrate it. |
| | | 2 | pellet penetrated fabric and bounced without d maging the rubber backing sheet. |
| (7) | Fibre glass fabric 310 $g/m^2$ | 1 | pellet bounced after penetrating the fabric and punching the rubber backing |
| (8) | Kevlar fabric 220 $g/m^2$ | 1 | pellet bounced without penetrating the fabric, but partly damaging the yarns in the fabric and also damaging the rubber backing. |

Discussion.

When the target, supported with rubber sheets is impacted by the pellet, there will be a build up of force on the whole target including the fabric and the rubber sheets. The rate at which the force increases will depend on the number of rubber sheets supporting the fabric, as illustrated in fig. (14).

The build up of force with no rubber sheets at all, will be very excessive, and as the number of rubber sheets is increased, the build up of force gets less and less excessive.

The amount of energy absorbed by the system, until the maximum force is achieved, will depend on the number of rubber sheets supporting the fabric. Higher amounts of energy will be absorbed with a higher number of rubber sheets. So if the number of sheets is enough to absorb the pellet energy, the pellet will be stopped and it will bounce. If the number of sheets is not sufficient to absorb the pellet energy, the pellet will penetrate and hit the steel stopping plate, dissipating its energy in squashing its shape. When the shape of the pellet after impact was observed in the experimental tests, it was found that, irrespective of whether the target had been penetrated or not, the higher the number of rubber backing sheets, the less damage occurred to the pellet.

From table (1), it can be seen that the material with a low penetration strength, such as polyethylene, needs a higher number of rubber sheets for bouncing of the pellet. This is, in fact, also a result of the low energy absorption of polyethylene. In the case of Kevlar fabric, although the pellet did not penetrate, because of the remarkable penetration strength of Kevlar fabric, but the energy absorbed by the system in this case was very little, so that the pellet was smashed on the surface of the fabric and flattened its shape. So, for the system to create a lower impact force and at the same time provide resistance to penetration, it is recommended that the fabric should be compressible and at the same

time with a high penetration strength. The needle felt seems to be the type of target that fulfils these two requirements and accordingly it would meet a less number of rubber sheets as backing to provide bouncing of pellet without excessive build up of force. From table (1), the needle felt needed two rubber sheets for bouncing the pellet, and after impact, the pellet shape did not change very much, which indicates that this system absorbed a higher amount of energy,without excessive build up of force.

# Chapter 4

## Final Review.

### General background

The purpose of this section of the report is to review the work carried out under the contract (and under the earlier contract DAJA37-71-C-0554), to see what general lessons can be brought out, and to place it in the context of other work on the subject.

The use of textile materials as a protection against ballistic impact has a long history, and has been seriously studied by scientists and engineers for at least 30 years. Nevertheless it remains a poorly understood subject, and progress has largely come from empirical development of possible materials and constructions. It therefore seems worthwhile, at the risk of naivete, to re-state some basic principles. The features which have to be taken into account in a textile for this end-use are listed in Table 2. The concentration of our interest has been on the ballistic properties.

Has the optimum choice (or a sufficiently close approach to it) already been achieved? It is - was - plausible to argue that this has - had - been done with woven nylon fabrics, and that research would not yield further benefit. This leads to the following comments:

(i) it would be of value - albeit negative value - to show that the optimum had been achieved;

(ii) while it is possible that the optimum solution involves putting all the weight in one fibre material, the behaviour of composite systems has probably not been adequately explored, and may include the optimum;

(iii) there is more than one application, and understanding is needed to get the best solution to particular needs;

## Table 2

### Features to consider in ballistic resistance behaviour of textiles

A. Ballistic properties

(a) Stopping power (and extent of any damaging deformation during stoppage)

(b) Energy absorption from penetrating particles.

Both related to (a) particles of varying mass, velocity, shape, material, direction
(b) various use geometries.

B. Weight

The dominant requirement is optimisation of ballistic properties against weight.

C. Textile properties

Flexibility, porosity and other characteristics giving freedom of movement and compact in use.

D. Miscellaneous properties

Ease of fabrication, durability, moisture uptake, thermal and chemical resistance, etc.

E. Economics

of secondary importance.

(iv) most important, new fibes are becoming available, and so a new optimum is possible - the current contender is Kevlar, but there are rumours of others. (As the range of choice increases, the need for calculation, as an aid to optimisation, becomes greater).

The theoretical approaches to the subject, which have been made, are diverse and reflect the differing backgrounds of different research workers. This high-lights the central problem - the choice of the right starting point and the right line of approach. And one is not helped much by work in related fields, such as the extensive work on ballistic impact of metals. The real problems are too complex for complete exact solutions - though in a fundamental sense they are known to depend on the laws of mechanics and the material properties - and the approximations and idealisations adopted are related to the particular problem. Thus, once one goes beyond simple elasticity, the developed subject is known as "dynamic plasticity"; but good textile materials behave in the converse way, with a stress-strain curve of increasing slope. In metals Johnson (2) lays stress on the "plastic hinge", but in textiles the bending offers negligible resistance. And so the choice of idealisation - the art which leads to manageable simplification - differs in these and other ways.

Finally, in the general philosophy of approach, one must stress the importance of dividing the problem into its constituent elements, and then trying first to understand each separately, rather than at first lumping it all together in a confusing whole, even though realism dictates that the whole system and its interactions must ultimately be dealt with.

## The division of the problem

Figure 15 illustrates the three principal sub-divisions of the problem.

Firstly, there are the structure-property relationships of the materials used - fibres assembled in woven, knitted or nonwoven structures. This is a large subject in itself, in which considerable progress has been made over the last 30 years. The most fruitful approach is hierarchical:

$$\left.\begin{array}{c}\text{properties of (n-1) level}\\ +\\ \text{structure of n level}\end{array}\right\}\ \text{properties of n level}$$

In this way, a mechanical analysis of any level is capable of general application and is not restricted by details of structure at lower levels. In the context of the present problem a fabric (the level n) would be regarded as a sheet with a set of properties as a two-dimensional continuum. One would move down to detailed treatments of woven, knitted or nonwoven fabrics (and then to yarns, to fibres, and to fine structure) to gain insights into the determination of the sheet properties - or alternatively one would rely on experimental measurements of sheet properties. But progress in this area is only worthwhile insofar as the needs at the application level (n + 1) are understood.

So secondly - and this is what has turned out to be the centre of our interest - there is the deformation geometry. In reality, there would be a multi-layer assembly of fabric, made up into a garment by sewn seams, and supported (with rather poorly defined boundary conditions) on the body. The simpler experimental set-up, which apparently experience confirms as reasonably predictive, consists of one or more layers of fabric which are firmly clamped at a boundary (a 6-inch circle in our arrangements; a 30.5 cm. square in the apparatus of Wilde et al (3)) and, usually, free of any backing. The impact then causes a cone-like deformation perpendicular to the fabric plane. The deformation necessarily varies from place to place over the specimen, and so this is not a type of test which would be chosen for fundamental studies of fabric properties. It seems likely that, at

least for the circular, axi-symmetric small-strain, linearly elastic case there exists a solution, though it is not obviously accessible, and certainly there is no treatment of the large-strain, non-linear case in the textile mechanics literature. A clear understanding of the quasi-static penetration problem would seem to be a good pre-requisite to consideration of the dynamic problem.

The static penetration problem is illustrated in figure 6, and the following features may be noted:

(i) the problem has two distinct parts;

(a) the general deformation of the material, under a given load, which could be capable of solution by force-equilibrium or energy methods;

(b) the condition for local penetration, dependent on the local forces at the point of application of load - failure will certainly occur if the general breaking strain of the material is exceeded, but it may fail more easily since every rupture is a "jaw-break";

(ii) the energy absorption must be summed over the variable deformation of the whole specimen;

(iii) in addition to the transverse movement, there may be radial movement under the varying stress, but this will be impeded since it involves change of circumference.

A continuing study of the quasi-static penetration process is required.

The third element is the influence of the dynamic situation - the rate effects. This comes in a number of different ways:

(i) the variation in load as applied by an impacting mass which is progressively slowed down (as distinct from the constant rate of deformation of an Instron test);

(ii) the influence of rate on isothermal fabric properties;

(iii) the effect of change of temperature due to energy dissipation;

(iv) the contributions of inertial forces due to the weight of the fabric (or any extra loading) even as it goes through a succession of quasi-static equilibrium positions;

(v) the effects of wave propagation and reflection;

(vi) the onset of "critical velocity" conditions, when the wave cannot propagate and penetration will occur with little energy absorption.

All these rate factors need to be taken into account separately. In the past, there has perhaps been a tendency to place too much emphasis on the wave propagation problem which is certainly a dramatic feature of photographic studies of the phenomenon.

The aim of academic study of the problem is to derive an overall theoretical approach to the problem which as indicated in figure 15 will link the three contributing factors together and lead to successful modelling and prediction of behaviour. Experiment (in the laboratory) and experience (in field trials) help in understanding, and thus to hopeful lines of theoretical development, as well as providing an alternative course for the choice of specifications for use.

There is one remaining division of the problem, which was stressed in the conclusion of the report by Hearle and Purdy (4). This is illustrated in the modes of response shown in figure 16. As the impacting energy is increased there is a discontinuity at the point at which complete penetration occurs. For high velocities, energy is only absorbed during the increase to the maximum load, which is the breaking load of the system, giving the response shown in curves A and B. But at lower impact energies, there is further energy absorption during a period of decreasing load, which may stop the projectile or fling it back, as indicated by curves, C, D.

The curves B and C are on either side of this discontinuity, and show the change in energy absorption which is shown practically in figure 4 of the paper by Wilde et al (4) and figure 11 of our 1974 report. Since the projectile must be moving forward with maximum deceleration at the point of maximum force it is impossible (except with an unusual local failure response) for a projectile to emerge except at high velocity.

(Note: the above argument, which fits with the observed behaviour does not appear to be valid for impact on a light, elastic material - again there is a need to clarify the simple fundamentals).

## Conclusions from experimental work.

The report by Hearle and Purdy (4) was concerned with the response of needled fabrics. A feature of more general importance is the complex shape of the deforming material in both static and dynamic penetration. The needled fabrics show poor recovery from deformation, and so the cross-sections in figures 9 and 19 of the 1971 report, are probably a reasonable indication of the nature of the deformation under load: they show cones which are concave outwards. The high-speed photography (figures 10 to 15) shows more complicated shapes, with convex and concave portions. But, at least, the real deformation is not a straight-sided cone.

From the experimental work included in the two reports under the present contract, the following general conclusions may be drawn.

(i) Until the critical level for non-penetration is reached, there appears to be a linear reduction in emerging velocity with number of layers (1974, fig. 10)*. Note that this is not a constant energy absorption in each layer, which would give a linear variation of $v^2$.

(ii) The most effective materials are woven, knitted and needled nylon and woven Kevlar, with paper, polyethylene film and bonded fabrics being the least effective.

*References to figures in the first report, Hearle and Sultan (1) will be given in this way.

(iii) The good materials show considerable overall deformation, while the poor ones show localised deformation (see 1974, figure 12).

(iv) The high-energy absorption shown in tensile tests by yielding materials is not shown in penetration tests, whereas the locking materials are better (see 1974, figure 20).

(v) There is a good correlation between ballistic penetration energy (of course, at the velocities of our experiments, namely 146 m $s^{-1}$) and the slow penetration energy (see 1974, figure 21).

(vi) The strength-bulge product gives a simple correlation with slow penetration energy (see 1974, figure 22).

(vii) The ratio of either slow penetration energy or ballistic energy absorption to work of rupture in a tensile test increases rapidly with a decrease in work factor, thus locking materials are preferable to yielding ones (see 1974, figures 23 and 24).

(viii) Penetration force is little affected by target diameter, indicating that it is a localised effect; but the magnitude of deformation and the energy absorbed increase rapidly with diameter in locking materials where there is considerable general deformation, but change little in yielding materials where the whole deformation is localised.

The influence of the shape of the load-deformation curve is confirmed by the highly approximate theory of quasi-static deformation developed in this report. In view of the experimental correlations, it seems justifiable to draw conclusions about dynamic impact (at least at moderate velocities) from a study of the quasi-static effects; Vinson and Zukas (5) take the same view.

A comparison of theoretical approaches.

As indicated earlier, there have been a variety of theoretical approaches, and it will be of value to compare them. Because of the difficulty of the total problem, simplifications are necessarily introduced, and these vary according to the temperament, background, time and particular purpose of the worker. It is valuable to have a diversity of approaches; and criticism, which includes self-criticism, should not be taken amiss. Progress will only come as different avenues are explored, and eventually linked together. The one general point of agreement is that the problem has not yet been solved and that it is difficult.

(a) Ipson (6) followed by Hearle and Purdy (4)

Ipson tackled the problem of predicting the variation of force with displacement (and hence of other related quantities) by adapting a one-dimensional solution of the wave problem to the problem of a radial wave. This led to the expressions

$$V_p = V_o \exp \left[ - \frac{1.86 \pi \rho T R}{M_p} (wt)^{3/2} \right]$$

where $V_p$ = projectile velocity at time t

$V_o$ = initial projectile velocity

$\rho$ = mass density

T = fabric thickness

R = projectile radius

$M_p$ = projectile mass

W = transverse wave velocity

Hearle and Purdy (4) following in the spirit of Ipsons idealisations which were Hookean and constant in parameters, showed that this led to the expressions:

$$V_o, \max = K R^{2/3} (M_f/M_p)^{1/3} W^{1/2}$$

where $V_o$,max is maximum velocity for non-penetration

K is a constant.

$M_f$ is fabric mass/unit area

W is work of rupture of fabric

The nature of the process assumed by Ipson is shown in figure 17. Apart from the obvious idealisations, there is a major difference between the response of one-dimensional and two-dimensional materials. In a thread, the longitudinal tensile wave with its inward movement of material occurs without further deformation; but in a sheet, the circumference reduces as the material moves into the centre (at the radial particle velocity of figure 17) and will be impeded by the further fabric deformation which is required. This is probably a good reason for rejection of these approaches.

(B) Hearle and Sultan (this report)

In contrast, the theory in this report is a first crude attempt at a non-linear treatment of the quasi-static geometry of deformation. It thus allows for real fabric stress-strain curves, but is grossly over-simplified in equation (1) by considering radial tensions (and tensile deformation) only, and then using a geometrical model of deformation. There is a lack of internal consistency because of unbalanced forces at zone intersections (balanced in reality by circumferential forces). There is also an assumption of no radial displacement and a neglect of fabric anisotropy. Nevertheless, the predictions are instructive, and with modest effort the treatment could be further developed.

(C) Roylance et al (7)

Roylance, Wilde and Tocci describe a treatment of the transverse impact of a one-dimensional thread by a computational method developed by Davids et al (8) and referred to as "direct analysis". The system is

divided into finite elements and then the detailed response computed sequentially in time stops. This is clearly an effective and valuable method of handling one-dimensional problem which have previously been difficult to deal with.

They extend this to the sheet problem by treating the fabric as a network of elements joined at nodes. One difficulty is then that the computation becomes very long. But a more serious criticism, in my view, is that a net is not a valid or useful model. The real deformations involve a more complex fabric deformation with crimp interchange, shear and yarn extension, and, both in terms of physical reality and the hierarachical approach to problems of the mechanics of textile structures, are better treated as being deformation of a sheet with defined continuum properties. Except in very open structures the deformation cannot be regarded as travelling along linear elements of a network to nodes.

(D) Wilde et al (3)

In a deliberate simplification, Wilde et al consider only the threads passing through the impact zones and so get a pseudo-one-dimensional problem of two orthotropic sets of threads. The simplicity of the treatment make this an instructive model, but it would be of doubtful validity except for materials of very low moduli away from the principal orthotropic axes.

(E) Vinson and Zukas (5)

Vinson and Zukas have based a treatment on the well-developed conical shell theory. It is assumed to be a membrane problem which can be represented by a straight-sided cone. This leads to a quasi-static solution of the equilibrium of force in the cone, based on a set of standard equations, which includes the elastic modulus as a parameter.

In the absence of experimental data on the variation of modulus with rate of deformation, they use the analytical treatment of the one-dimensional problem to extract information from the observed wave propagation in fabric impact. For reasons already given, this latter part of the treatment seems counter-productive, and it would be better to stick with assumed values of moduli.

The shell theory has the defect, which we feel is serious, that it is based on a straight-sided cone. Their predictions include impossibly high values of fabric strain.

## (F) The future.

Most of the above approaches could be taken as starting-points for a better treatment, with the least satisfactory features of the models being progressively dropped. My own inclination would be to improve the treatment of the non-linear quasi-static penetration problem either by a specific treatment or by using the finite element method currently being developed by Lloyd at UMIST , and then to introduce rate effects, inertial effects and wave propagation.

Combined with the theoretical work experiments on a range of fabrics with a suitably instructive range of parameters should be carried out.

# Appendix

## A note on quantities and units

The subject of this work involves some unfamiliar quantities, and, in the current state of flux, some problems in choice of units.

The basic quanties involved, with some possible units, are:

| | SI | CGS | Other | Imperial |
|---|---|---|---|---|
| diameter of test specimen | m | cm | | in |
| area of test specimen | $m^2$ | $cm^2$ | | $in^2$ |
| areal density of fabric | $kg/m^2$ | $g/cm^2$ | $g/m^2$ | $oz/yd^2$ |
| mass of fabric | kg | g | | lb |
| penetration force | N | dyne | gf | lb.wt. |
| penetration deformation | m | cm | | in. |
| penetration energy | J | erg | kg.cm | ft-lb. |
| mass of particle | kg | g | | oz. |
| velocity of particle | m/s | cm/s | | ft/sec. |
| energy of particle | J | erg | kg.cm | ft-lb. |
| length of tensile test specimen | m | cm | | in |
| width - - - - - - - - - - - - - - | m | cm | | in |
| elongation- - - - - - - - - - - - | m | cm | | in |
| force on - - - - - - - - - - - - - | N | dyne | kg.f | |
| work of rupture- - - - - - - - - - | J | erg | Kg.cm | ft-lb |

The problems occur with normalisation which may be done for <u>either</u> relevance to practical use <u>or</u> experimental convenience <u>or</u> theoretical simplicity: these requirements may conflict. Some quantities and units are given below.

(a) Tensile test results, normalised as 2-D sheet properties.

| | SI | other |
|---|---|---|
| "stress"= force/width (modulus, strength) | $Nm^{-1}$ | gf/cm, lb.wt/in. |
| "strain"= elongation/length | dimensionless | |
| energy per unit area | $Jm^{-2}$ | |

(b) Tensile test results, normalised as material properties on a "weight" basis (in fibrous assemblies, characterisation on a volume or cross-sectional area basis is fraught with difficulties)

*Specific stress = force/linear density N/kg $m^{-1}$ gf/tex=Km
gf/den.

*(tenacity or specific strength, $= \dfrac{\text{force}}{\text{width x areal density}}$

*specific modulus $= \dfrac{\text{conventional stress (=force/area)}}{\text{density}}$

| | | |
|---|---|---|
| strain | dimensionless | |
| *energy per unit mass | J/kg | gf/tex |

(c) penetration properties (where choice of quantities is still debatable).

| | SI | other |
|---|---|---|
| "strength"- this is locally determined and is best normalised as: | | |
| $\dfrac{\text{force}}{\text{areal density}}$ | $N/kgm^{-2}$ $=(m^3\ s^{-2})$ | $gf/gm^{-2}$ |
| "bulge strain" - this increases with specimen diameter and is normalised as: | | |
| $\dfrac{\text{transverse deformation}}{\text{specimen diameter}}$ | dimensionless | |
| area strain - this quantity, not used, might be useful: | | |
| $\dfrac{\text{increase of area}}{\text{original area}}$ | dimensionless | |

*these quantities are dimensionally identical and so units are interchangeable. The basic unit is $m^2\ s^{-2}$.

"penetration energy"

normalised as: $Jkg^{-1}$

$$\frac{\text{energy}}{\text{mass of specimen}}$$

(this quantity comes out with same units as in other test geometries i.e. $m^2\ s^{-2}$)

"penetration stiffness":

this may be normalised as:

$$\frac{\text{force/areal density}}{\text{bulge strain}} \qquad N/kgm^{-2}$$

but this does not allow for the fact that more force will be needed with specimen of large diameter.

By analogy, a specific stress f could be defined as:

$$f = \frac{d\ (\text{energy/mass})}{d\ (\text{bulge strain})} \qquad Jkg^{-1}$$

then specific modulus

$$= \frac{d\ (\text{specific stress})}{d(\text{bulge strain})} \qquad = N/kgm^{-1} \qquad N/tex$$

$$= \frac{d^2(\text{energy/mass})}{d(\text{bulge strain})^2}$$

$$= \frac{(\text{diameter})^2}{\text{mass}} \times \frac{d(\text{force})}{d(\text{deformation})}$$

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3. A.F. Wilde, D.K. Roylance and J.H. Rogers, Textile Res.J., 43, 753 1973. (See also A.F. Wilde, Textile Res.J., 44, 772, 1974).

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6. T.W. Ipson and E.P. Wittrock. U.S. Army Contract No. DA19-129-AMC-157(N) Technical report 67-8-CM July, 1966.

7. D. Roylance, A. Wilde and G. Tocci, Textile Res., 43, 34, 1973,

8. P.K. Mehta and N. Davids, AIAAJ. 4, 112, 1966.

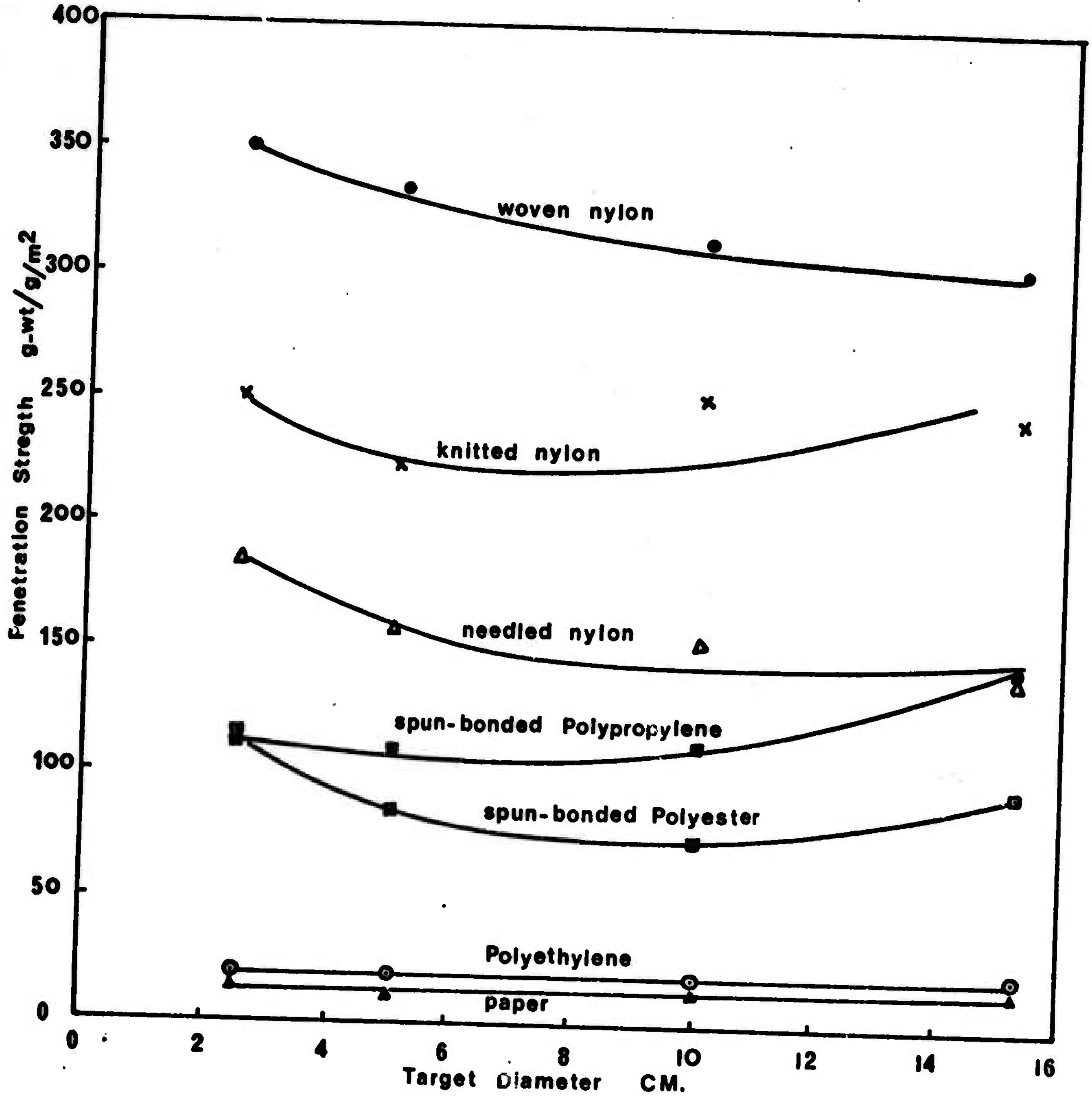



FIG. 1 Target Diameter Against Penetration Strength

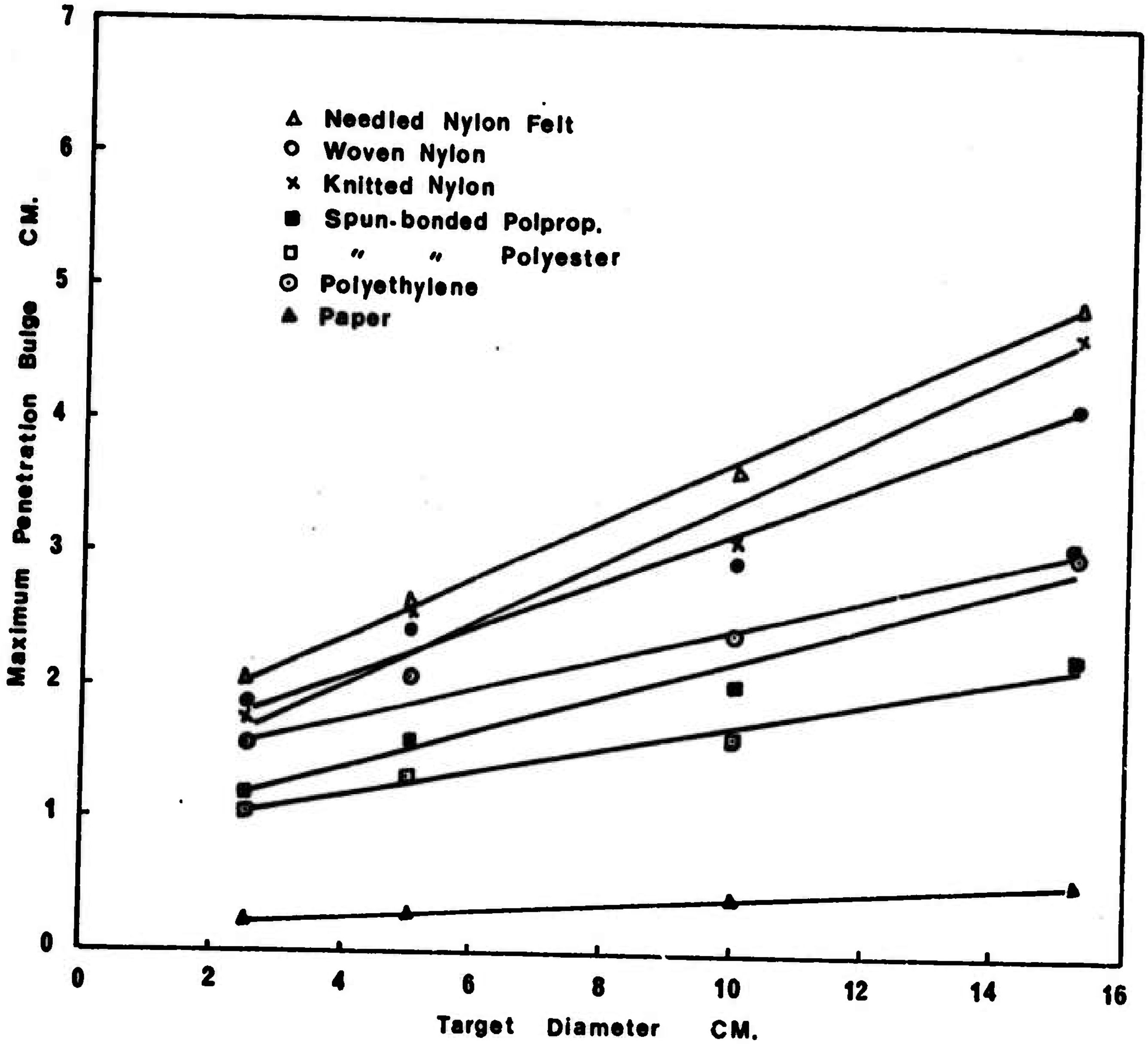



FIG. 2 Effect Of Target Diameter On The Maximum Bulge In Slow Penetration

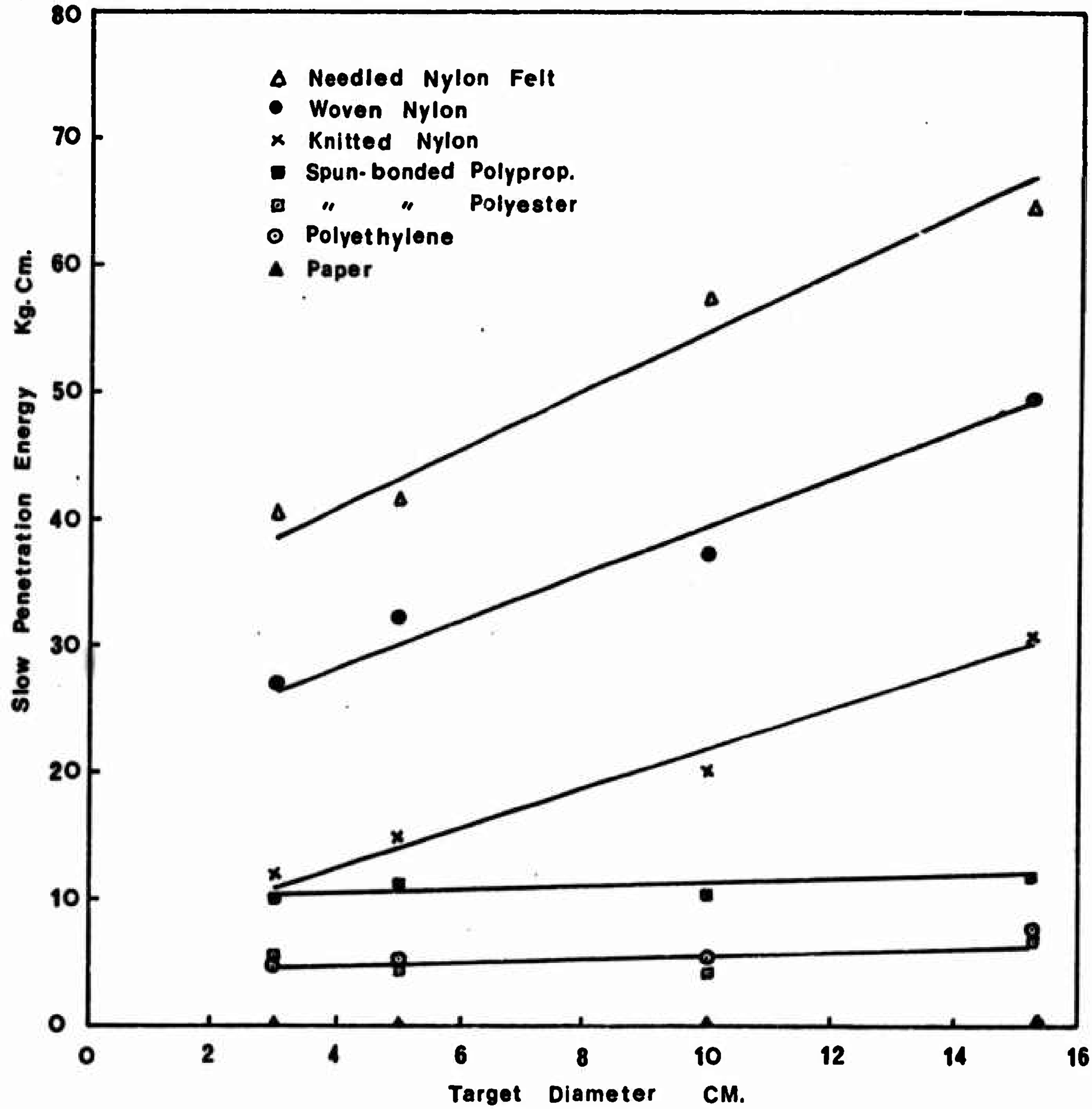



FIG. 3 Effect Of Target Diameter On Slow Penetration Energy

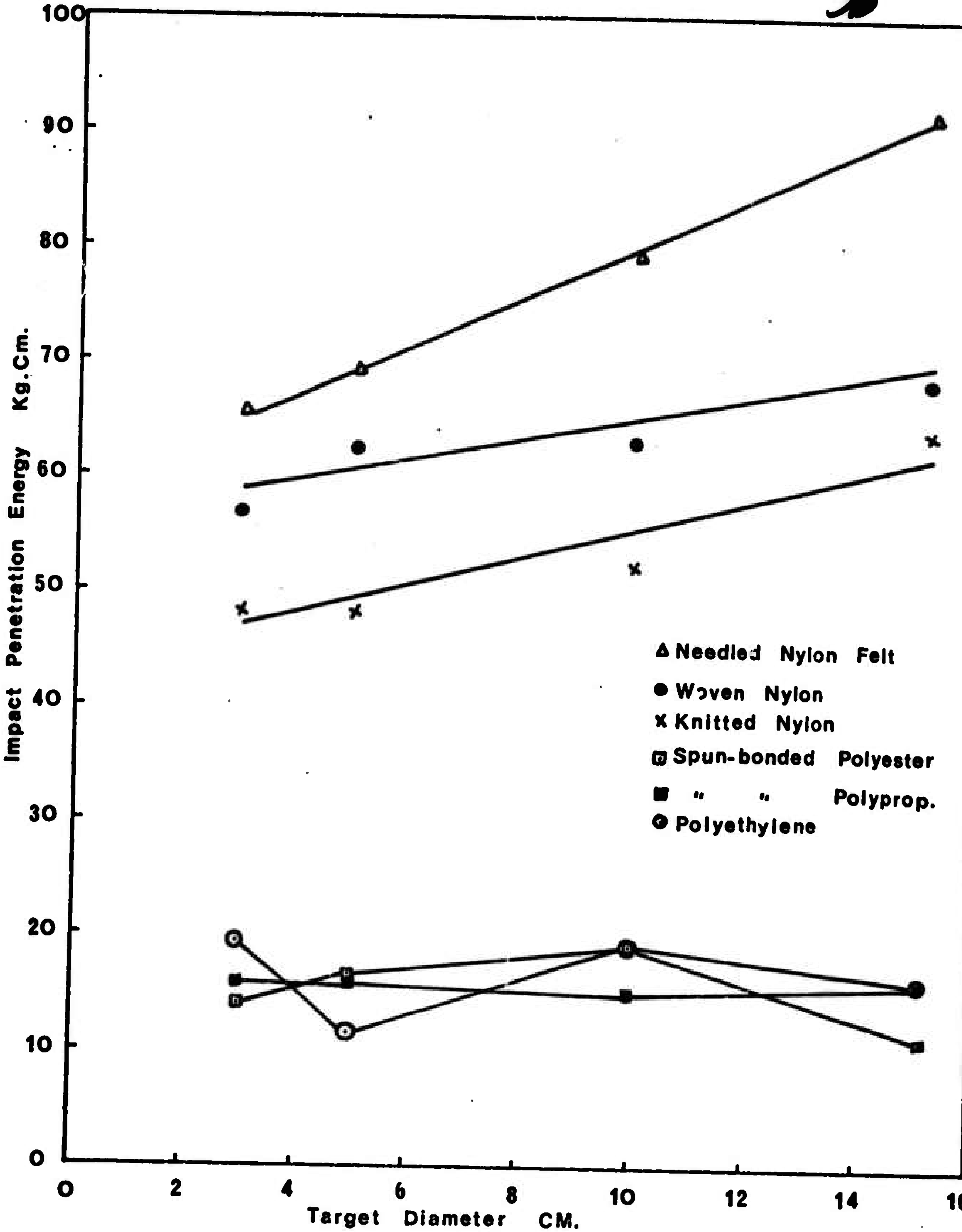



FIG. 4 Effect Of Target Diameter On Impact Penetration Energy

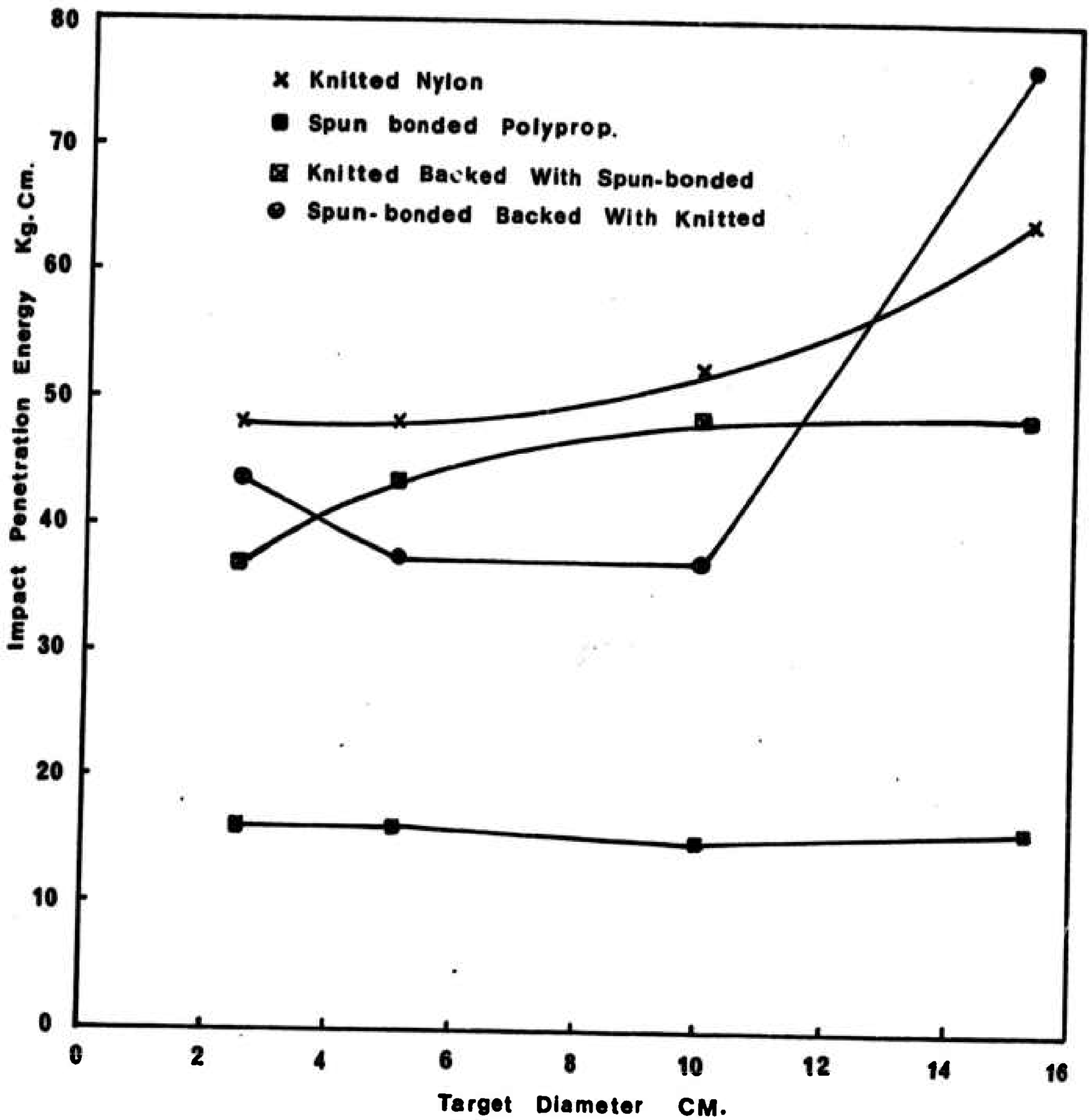



FIG. 5 Impact Energy Absorption By Composite Targets

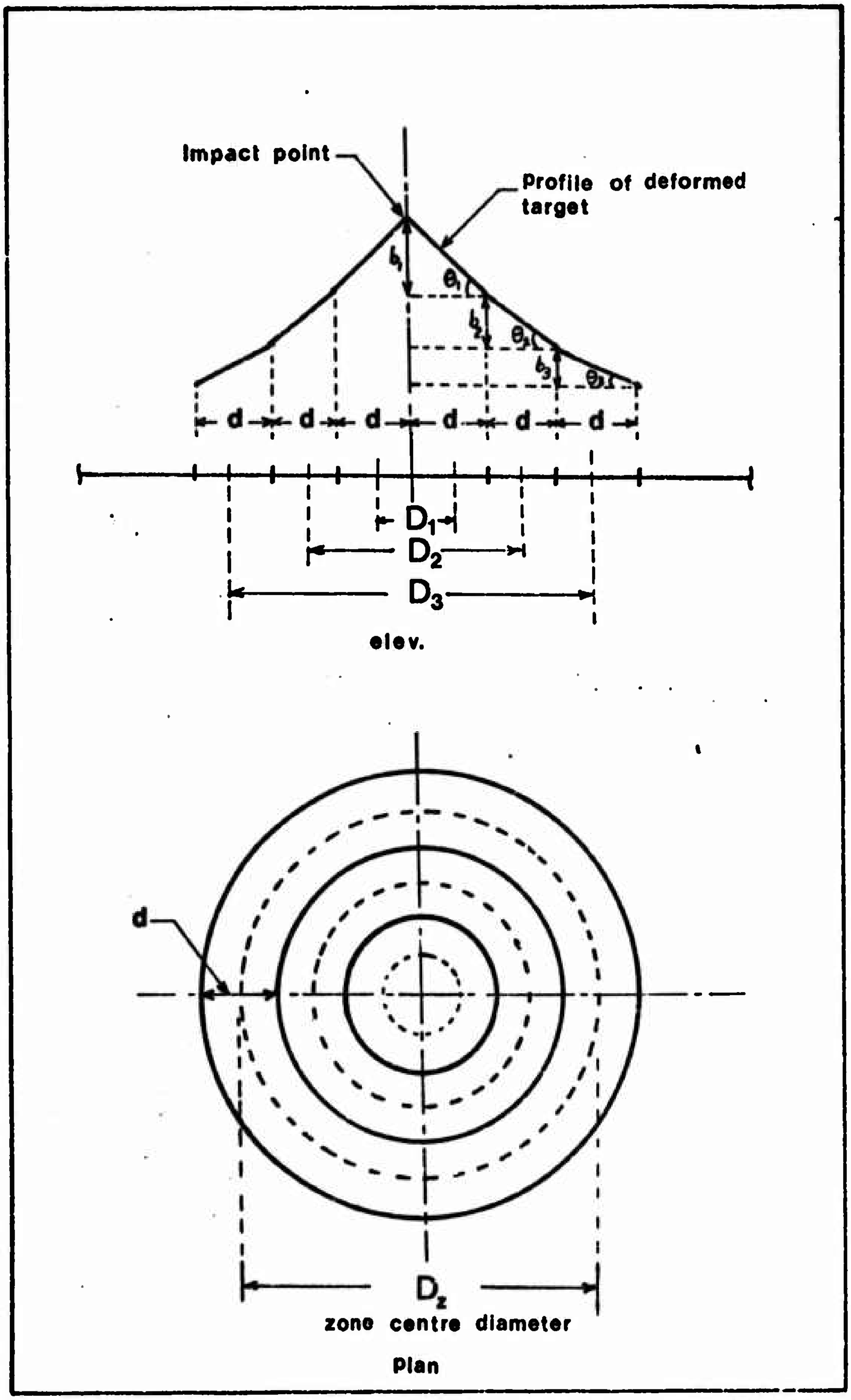



FIG. 6 Division Of Target Into Concentric Zones

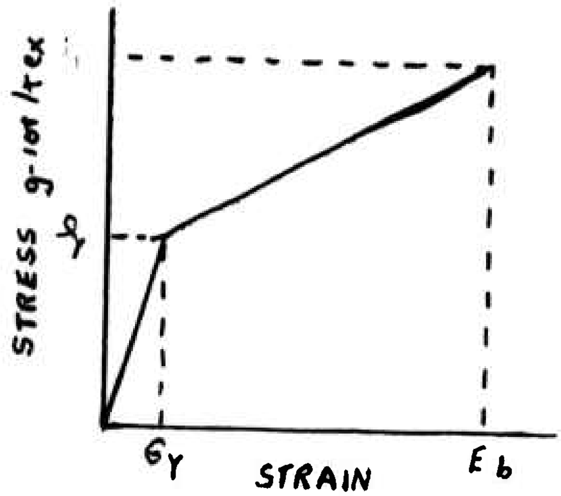



FIG 7 IDEALISED STRESS-STRAIN CURVE

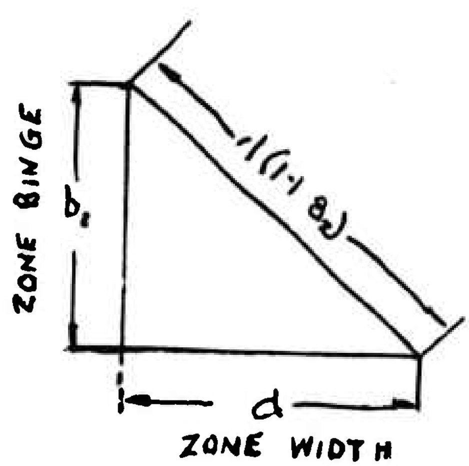
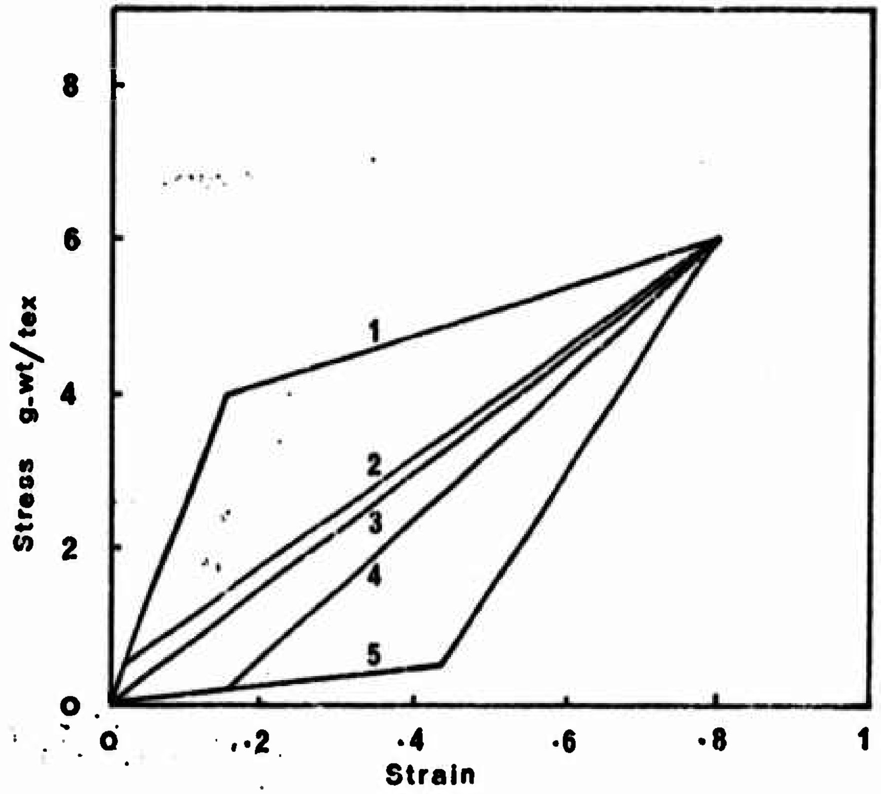
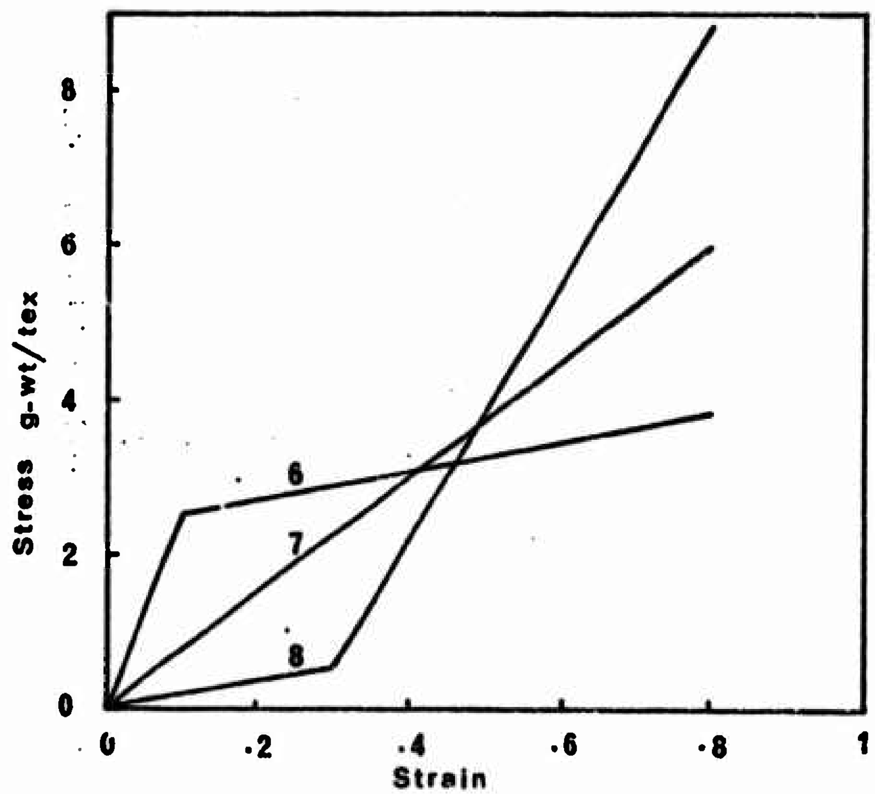



FIG 8 ZONAL BULGE AND WIDTH




| Curve NO. | Work factor |
|---|---|
| 1 | 0·74 |
| 2 | 0·53 |
| 3 | 0·5 |
| 4 | 0·43 |
| 5 | 0·27 |
| 6 | 0·77 |
| 7 | 0·5 |
| 8 | ·34 |

a-curves with the same strength and extension




b-curves with the same work of rupture

FIG. 9 Different Shapes Of Stress-Strain Curves

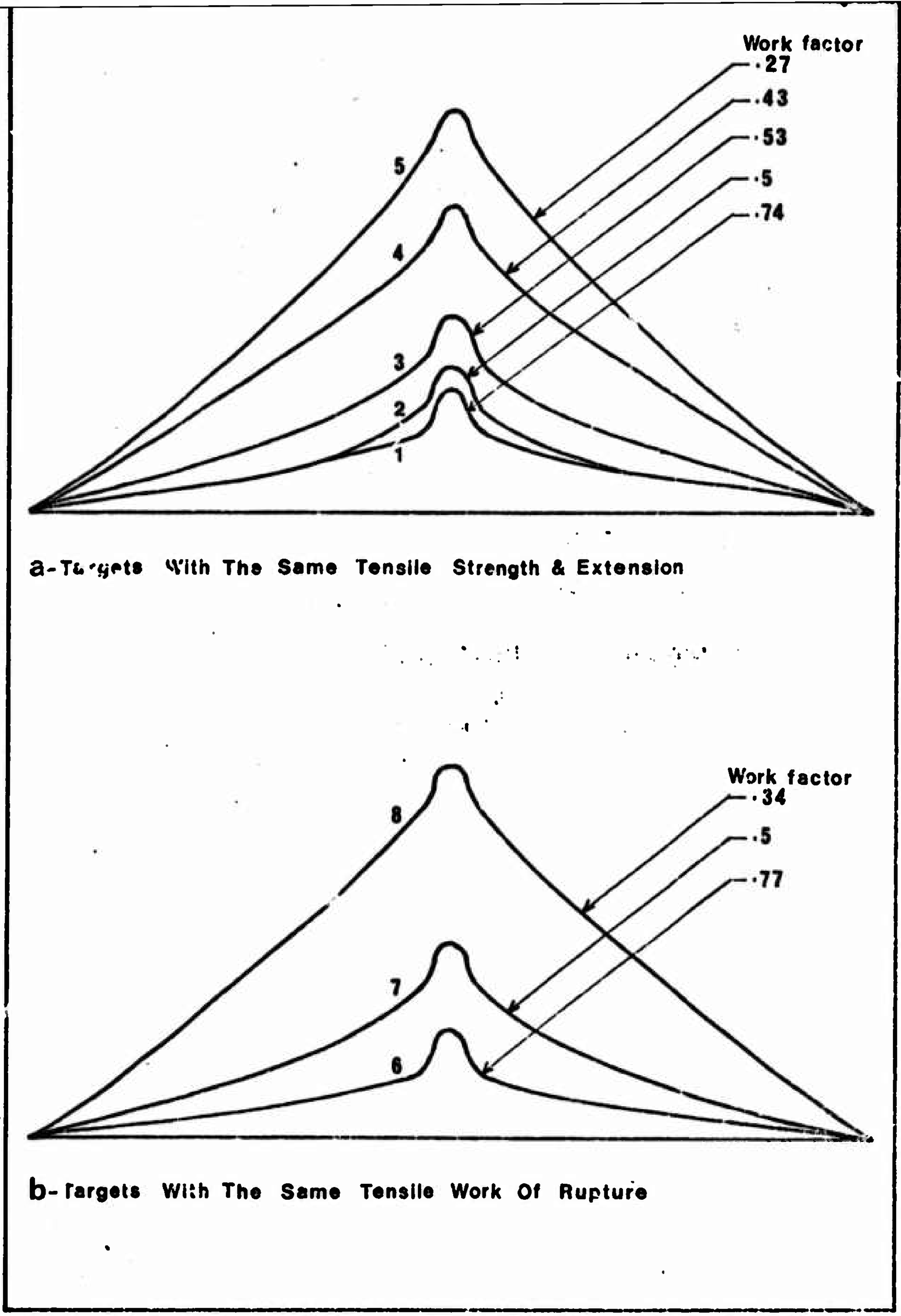
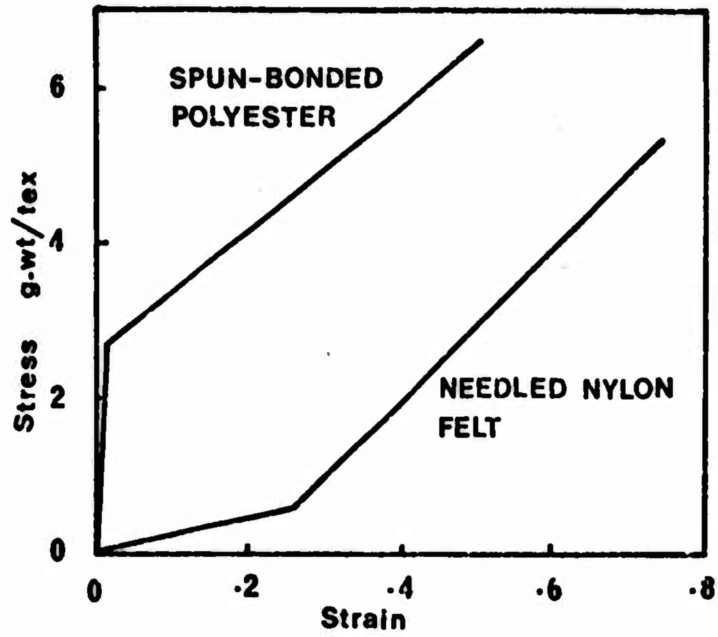



FIG.10 Theoretical Target Deformation Due To Slow Penetration




EXPERIMENTAL STRESS-STRAIN CURVES FOR TWO DIFFERENT TARGET MATERIALS

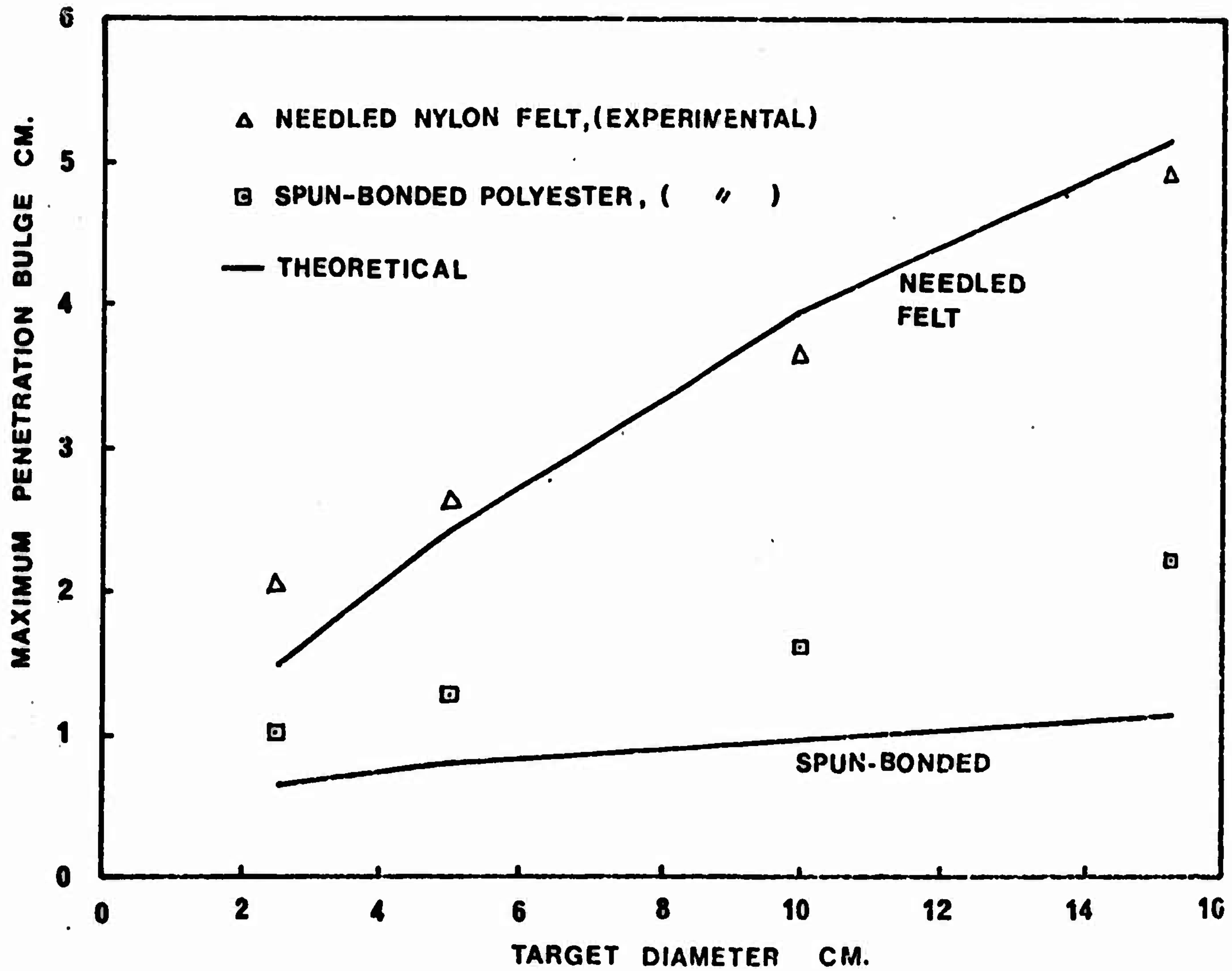



FIG. 11 Comparison Between Theoretical And Experimental Bulge In Slow Penetration

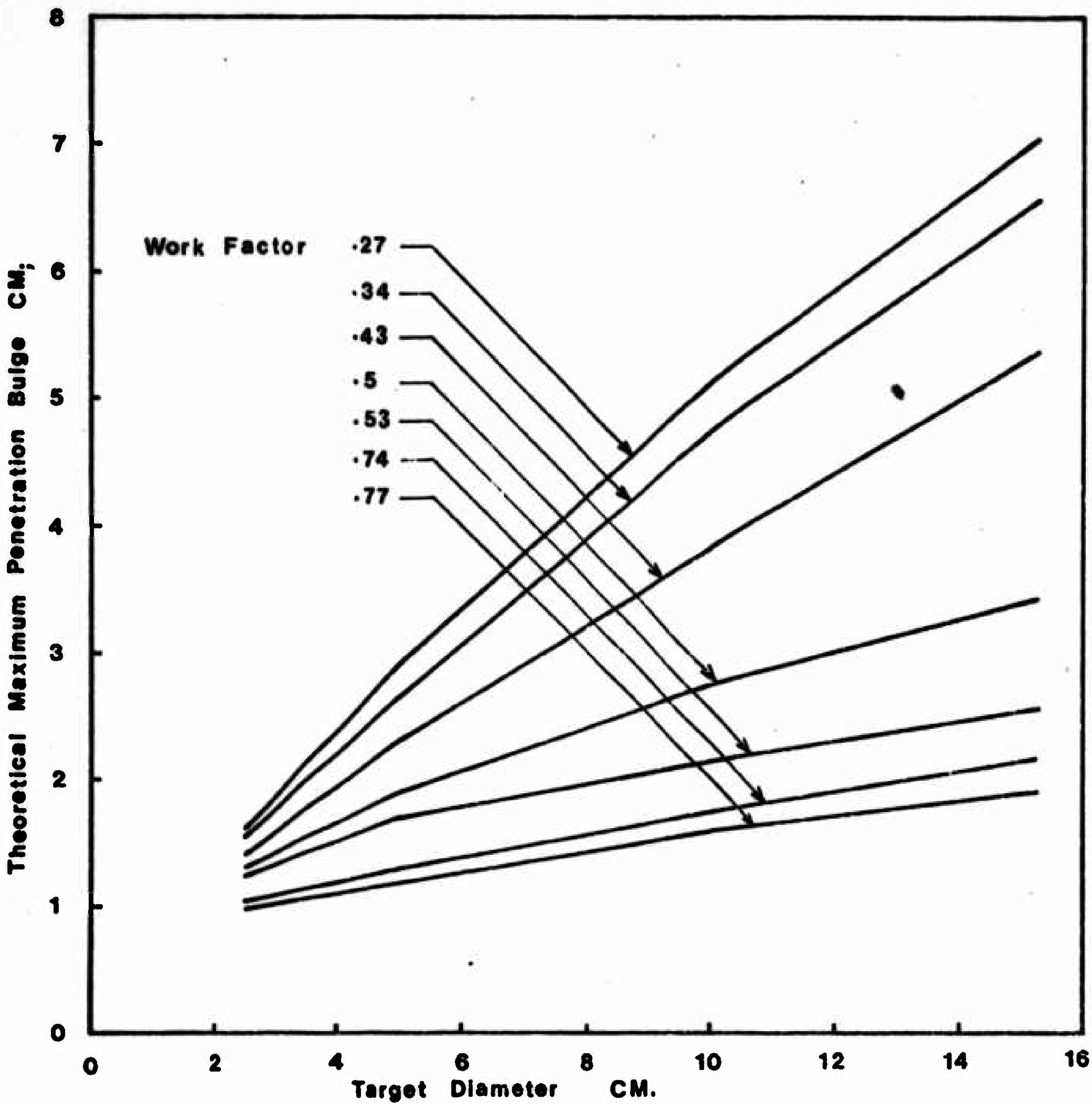



FIG.12 Theoretical Relation Between Target Diameter And Maximum Penetration Bulge

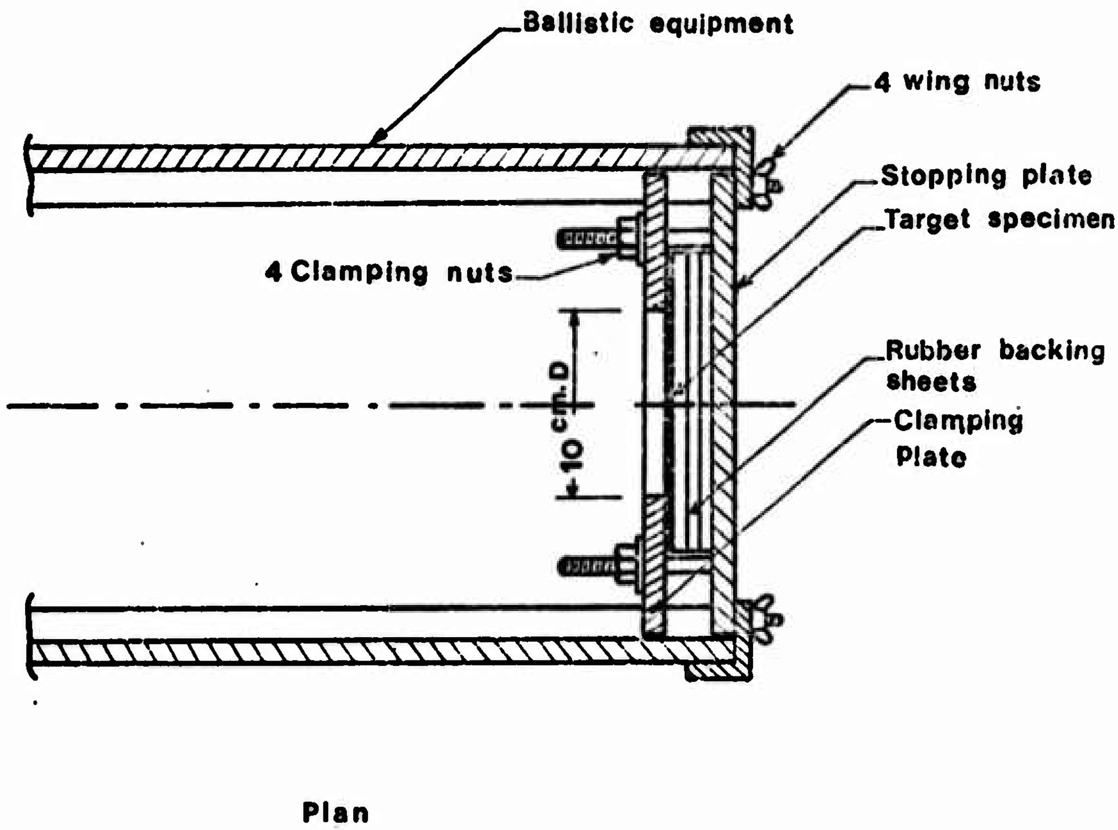



FIG. 13 Method Of Holding Supported Targets

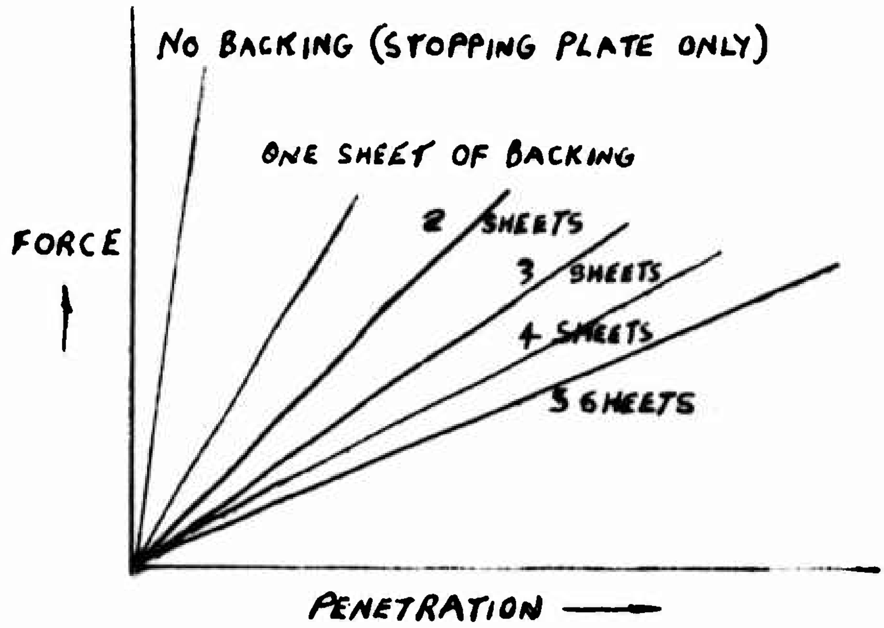



FIG 14 EFFECT OF NUMBER OF RUBBER SHEETS

# Penetration Dynamics of Textile Materials

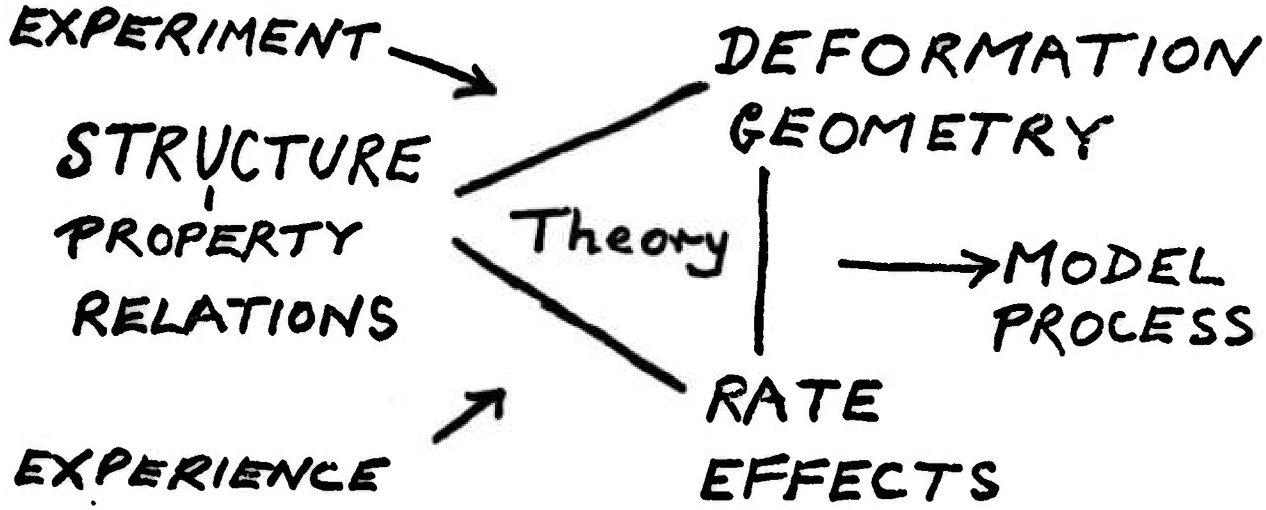



FIGURE 15

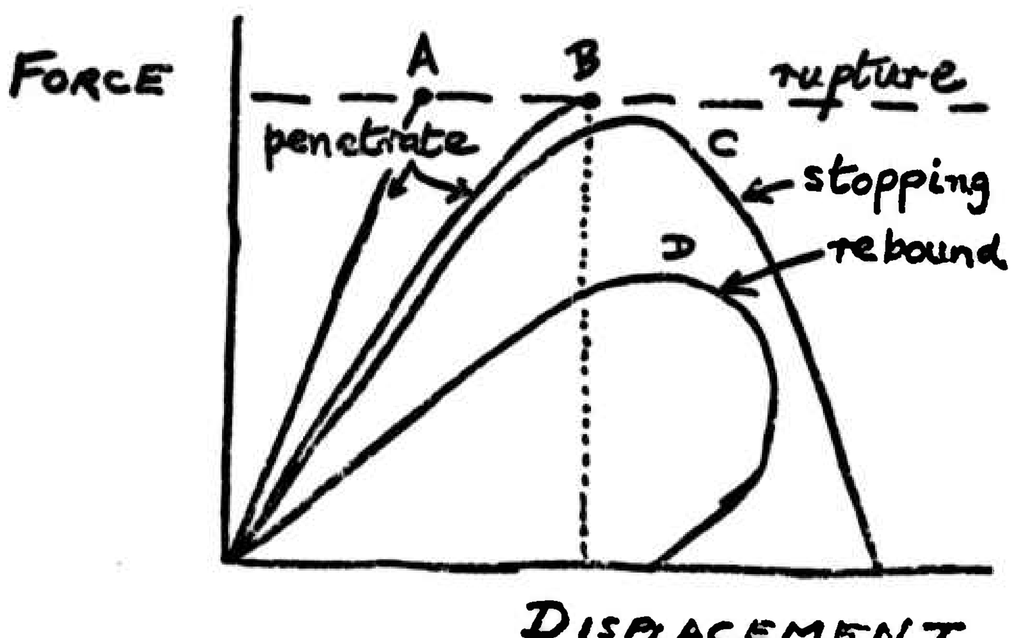



FIGURE 16

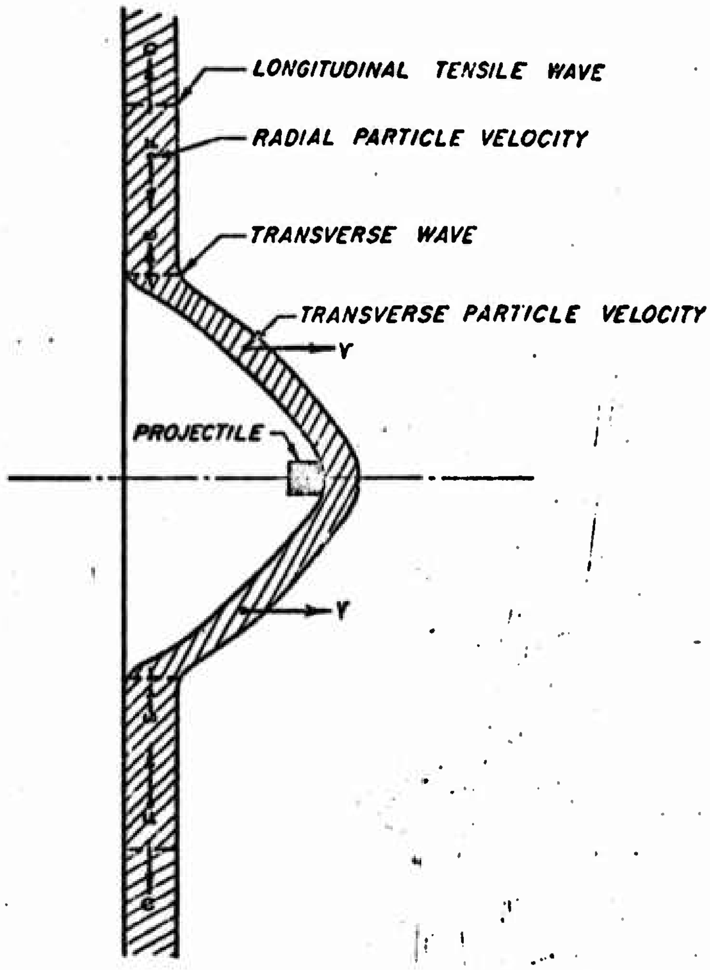



**Figure 3.** Illustration of the Wave and Material Behavior which Occurs during Ballistic Impact of Non-Rigid Felts

(from Ipson and Wittrock, ref. 6)

FIGURE 17